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Trace and Rare Earth Element (REE) Content of Clinopyroxenes in Peridotites from Supra-Subduction Zone Ophiolites: Implications on Melting and Enrichment Processes in Island Arcs

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We measured trace element and REE contents of clinopyroxenes (cpx) in peridotites from ophiolites from the Hellenic Peninsula (Vourinos, Pindos, Othris and Bulqiza). Compared to both abyssal peridotites and harzburgites from the Oman ophiolite the Hellenic peridotites have a highly depleted mineralogy (<1% modal cpx) and the cpxs have extremely low concentrations of Ti (10-150 ppm) and heavy REE (Yb = 0.1-1.4 times chondritic). The light and middle REE, Zr and Sr contents of the cpx show enrichment (i.e. La = 0.02-2 times chondritic, Zr = 0.4-1 ppm) compared to cpx from abyssal peridotites. Our data falls in the field of previous studies of modern arc peridotite;[1] Bonnatti unp.) suggesting these samples come from the sub-arc mantle. Lava chemistry of the ophiolites suggests that these complexes originated above a subduction zone (i.e. Supra-Subduction zone ophiolites, SSZ).[2]

Dry melting of a source similar to a MORB source cannot generate the extreme depletions in the cpx; the last residual cpx in dry melting models has higher Ti (150 ppm) and HREE (Yb = 1 times chondritic) content than the average cpx from the SSZ peridotites. We propose that these high degrees of depletion can be achieved during hydrous melting (as suggested by others for the mantle wedge above a subduction zone). The rate of melting of cpx during hydrous melting is expected to be less than in dry melting. The rate of orthopyroxene (opx) consumption increases as opx melts and produces both olivine and melt. These changes in melting modes allow for larger degrees of total melting and larger depletions in Ti and HREE in the cpx before cpx is exhausted from the residual mineralogy. The enrichments in LREE, MREE, Zr and Sr are modeled by maintaining a constant flux of a slab-derived fluid component in the mantle wedge during melting. Ti and the HREE are not mobile in this fluid and are not enriched in the mantle peridotite. The continuous flux is necessary to sustain hydrous melting in the sub-arc mantle during the complete melting range. This is in agreement with recent U-Th disequilibria studies in island arc volcanics suggesting a small time interval between fluid flux and lava eruption.

Our calculated composition of the fluid is in agreement with previously published estimates which are based on mass balance calculations of island arc volcanics.

We suggest that a constant flux of a slab-derived fluid in the mantle wedge above a subduction zone is necessary for both the enrichments and depletions seen in modern and ancient arc-derived peridotites.

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Element Transport from Subducted Slab to Juvenile Crust at the Mariana Arc

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An extensive suite of sub-aerial, recent lavas from the Mariana arc have been analyzed for major and trace elements by XRF and ICP-MS, and for radiogenic and U-series isotopes. This high quality dataset reveals geochemical systematics consistent with melting of an originally highly depleted mantle source to which has been added sediment and "aqueous-fluid" components from the subducting slab. Sediment and "aqueous-fluid" additions are discrete events. The sedimentary flux has some significantly fractionated trace element ratios compared to bulk subducted sediment, in particular showing marked enrichments of large ion lithophile elements (LILEs) relative to high field strength elements (HSFEs). For most of the "incompatible" elements considered in this study, the sedimentary contribution is the dominant component in the elemental budgets of the lavas. Thus within arc chemical variations are largely the result of variable additions of the sedimentary component along the length of the Mariana arc. The "aqueous-fluid" flux into the sub-arc mantle is thought to be the result of dehydration of the altered oceanic crust. This "aqueous-fluid" is fluxed into the sub-arc mantle occurs at least 350,000a after the addition of the sedimentary material. The U-rich aqueous-fluid produces U-excesses in the source of the arc lavas which on melting produces magmas with similarly large U-excesses. U-Th systematics imply a very short time (~10,000a) between addition of aqueous fluid to the sub-arc mantle and eruption of lavas at the arc front.

Geochemical Earth Reference Model: The Depleted Mantle

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The composition of the mantle source of mid-ocean ridge basalts (MORBs), has been evaluated in the context of estimates for present chemical fluxes into and out of this reservoir. The primary sources of information on its composition are: (1) the composition of primary MORB magmas; (2) modeling of the melting process at mid-ocean ridges; (3) ultramafic xenoliths, peridotite massifs and ophiolites; and, (4) chemical and isotopic modeling of mantle-crust evolution, as well as degassing models based on noble gases.

That MORB source mantle, or depleted mantle (DM) as it is often referred to, is depleted in many important incompatible trace elements is well established. In contrast, moderately incompatible and compatible element abundances in this reservoir are similar to estimates for "primitive mantle" or bulk silicate Earth. Many (but not all) of the chemical and isotopic features of DM are

consistent with an origin by repeated melting of an initially primitive mantle to produce the continental crust. Thus, DM is considered to be, to first order, the chemical and isotopic complement of the continental crust.

The most important and best understood fluxes into and out of DM are the extraction of the oceanic crust and associated degassing at mid-ocean ridges, and the recycling of altered oceanic crust and sediments at subduction-zones. Other fluxes, such as inputs from a possibly-less-depleted lower mantle, or from enriched mantle domains, or those due to hypothesized delamination of continental lithospheric roots, can be modeled, but are strongly dependent on assumptions regarding the chemical and isotopic composition of these other domains.

Use of *Tillandsia Usneoidses* as Atmospheric Monitors for Heavy Metals

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As a consequence of ^{208}Pb being produced by the decay of ^{232}Th, ^{207}Pb and ^{206}Pb being produced by the decay of ^{235}U and ^{238}U respectively, and ^{204}Pb being entirely non-radiogenic, the isotopic composition of lead in nature is highly variable. Indeed, it is likely that, at some level, the lead from any mining district is isotopically different than lead from any other mining district in the world. Accordingly the isotopic composition of lead has been used to trace its source in geologic, archeologic, and environmental materials.

In a program initiated in 1997, the isotopic composition of lead deposited from the atmosphere over Florida and collected in rain samples by William Landing of Florida State University as part of a mercury study, have been isotopically analyzed. This began as a test of Landing's hypothesis that atmospheric deposition of mercury is the ultimate source of elevated mercury levels observed in aquatic animals in Florida (as well as in much of

the northern hemisphere) and that much of this mercury (and perhaps other heavy metals) is transported from across the Atlantic Ocean.

The isotopic composition of lead, when considered in terms of isotope ratios, fit with remarkable precision a binary mixture of lead having the same isotopic composition as that which dominates the North American atmosphere (know as Mississippi Valley type MV lead, after the source of most lead used industrially in the United States) and of lead of the type prevailing in the atmosphere of Europe and the Mediterranean area. Regardless of the exact sources, the values measured over Florida represent the same mixture as that measured out over the open Atlantic Ocean.

Specially constructed towers to sample rain are expensive and a high density network can not be expected. As an inexpensive way of achieving a high density network of collectors of atmospheric metals, *Tillandsia usneoidses* (Spanish moss) has been analyzed. The results show the same binary mixture of lead as do the rain samples, but with a slightly higher MV component. This higher MV component is thought to reflect the situation that all rain samples analyzed were collected during spring and summer months, when easterly derived air mass are most common, while the samples of *Tillandsia usneoidses* contain lead collected throughout the year. Alternatively the difference might be a consequences of the total lead loading being greatest during the spring and summer, and moss sampling the entire year records a larger influence of lead from local sources.

It is anticipated that isotopic analyzes of certain other elements in addition to lead in epiphyte plants can help identify sources of heavy metals in the atmosphere. With the high density network such epiphytes provide, regional contouring of isotopic values can permit the identification of local or point sources as anomalies on the atmospheric baseline we are now defining.

# Hf Isotope Constraints on Mantle Evolution

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The similarity of the Lu-Hf and Sm-Nd isotope system during most mantle differentiation processes makes the combination of $^{176}Hf/^{177}Hf$ and $^{143}Nd/^{144}Nd$ a very sensitive indicator of a select number of processes. New Hf-isotope data for a large number of ocean islands allows a reexamination of the importance of these processes and for the first time allows examination of the Hf-Nd-Pb isotope relations of oceanic volcanics. Except for HIMU islands, St. Helena and Tubaii, the Hf and Nd isotope ratios in ocean island basalts (OIB) are extremely well correlated. It is argued that crustal recycling (by either continental or oceanic sediments) most likely did not cause the Hf-Nd variations. The correlated $^{176}Hf/^{177}Hf$ - $^{143}Nd/^{144}Nd$ variations in OIB most likely represent the time integrated fractionations which are the result of melting in the presence of garnet. The Hf-isotope systematics of HIMU-type OIB are consistent with these basalts representing recycled oceanic crust and thus support the earlier hypothesis on the origins of HIMU basalts.[1-3]

Chondrites form an array that is at high angle with the OIB array (see Figure 1). This allows a choice in the $^{143}Nd/^{144}Nd$ and $^{176}Hf/^{177}Hf$ values for chondritic bulk earth. With a choice of bulk Earth at the extreme end of the OIB array the shift of OIB to higher $^{176}Hf/^{177}Hf$ can be explained by either isolation of a significant amount of basalts from the mantle for several billions of year or by fractionation and isolation of small amounts (<1%) of perovskite, during the early history of the Earth. The large range in Hf-isotopes for a limited range in Nd-isotopes in MORB can be explained by addition of small amounts (<<1%) of the perovskite material back into the MORB mantle. If chondritic BE is chosen to be internal to the OIB, the well correlated Hf-Nd isotope characteristics in OIB argue against the fractionation of perovskite during the early history of the Earth and the shape of the MORB field remains an enigma.
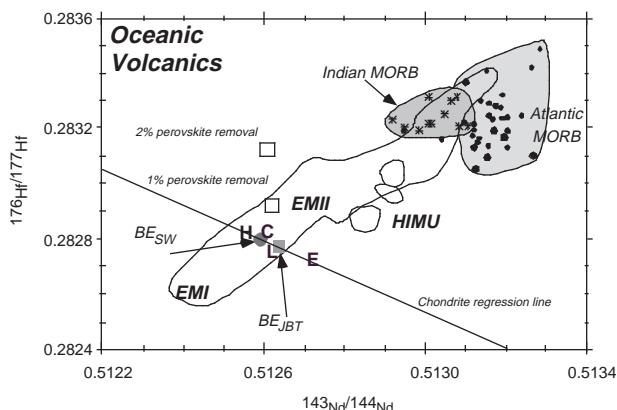
Figure 1. Hf-Nd isotope diagram showing the effect of removal of different amounts of perovskite on the composition of the silicate Earth. The squares indicate where the "residual" silicate Earth would plot after removal of 1 or 2% of perovskite. This model assumes removal and isolation of perovskite at least 4.0 Ga (giga annum-billion years) ago. Clearly 1% perovskite removal can explain the shift of the OIB array to high $^{176}Hf/^{177}Hf$ values. Chondritic Earth value from Reference 4. Perovskite partition coefficients $D_{Hf}=9.0$, $D_{Lu}=1.2$, $D_{Sm}=0.3$ and $D_{Nd}=0.15$ are derived from the studies of Kato et al.[5,6] Bold letters near the chondrite regression line represent the average for the different classes of meteorites: C= carbonaceous, E= enstatite, H = ordinary high Fe and L = ordinary low Fe. Data for Sm-Nd systematics of the chondrites are from References 7, 8, and 9.

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Trace Element Partitioning During the Initial Stages of Melting Beneath Mid-Ocean Ridges

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In the past year we have synthesized and doped three bulk compositions, and have run approximately twenty experiments in a piston cylinder apparatus for the purposes of determining phase equilibria at the lower limit of the garnet stability field (24 kbar) or of providing quenched crystal-liquid pairs (24-28 kbar) suitable for measurement of trace element partition coefficients by ion-probe analysis.

We have also spent considerable time and effort trying to resolve discrepancies between our data and those from other labs, in terms of both phase equilibria and partitioning. The phase equilibria study has been largely successful, but produced unexpected results. The experiments designed to provide material for trace element analysis were also successful, but new insights gained from the phase equilibria required some additional syntheses at 28 kb. And finally, irreconcilable differences between our garnet-liquid partition coefficients for Th and those reported by Beattie[1] have prompted us to reanalyze some of our experimental charges before completing revisions to our paper on the subject.

In the figure we show below our obtained melt compositions which fall within the within the 28-30 kbar field—this field also contains compositions from Takahashi,[2] Hirose and Kushiro,[3] Kushiro,[4] and Walter.[5] The figure clearly shows that our partitioning experiments are closer in composition to the lherzolite-melt system than any of the published partitioning experiments.

Comparison of liquids in equilibrium with lherzolite assemblages up to 30 kb (shaded fields)

and liquids produced in studies of U-Th partitioning between garnet and liquid (individual points - see legend). Compositions are projected from the wollastonite (CaSiO3) component onto the Ol-Ne(NaAlSiO$_4$)CA(CaAl$_2$O$_4$)-Qtz plane.

We have performed a number of tests and determined that the higher partition coefficients we found[6] for both compatible and incompatible elements are not artifacts of non-equilibrium. Reanalysis on smaller spots and use of sensitive indicators of melt inclusions (K and Rb) we have established that the measurements are correct. In addition, the dependence on P, T and composition that we found in our partition data is what is expected based on simple thermodynamics, while the results of other studies are incompatible with thermodynamic data.

Our new partition coefficients in combination with the new phase equilibria (most appropriate for the initial stages of melting) relax the extreme constraints from uranium-thorium disequilibria on mid-ocean ridge basalt genesis and reconcile the implications of excess [230]Th with melting models based on other geochemical and geophysical parameters.
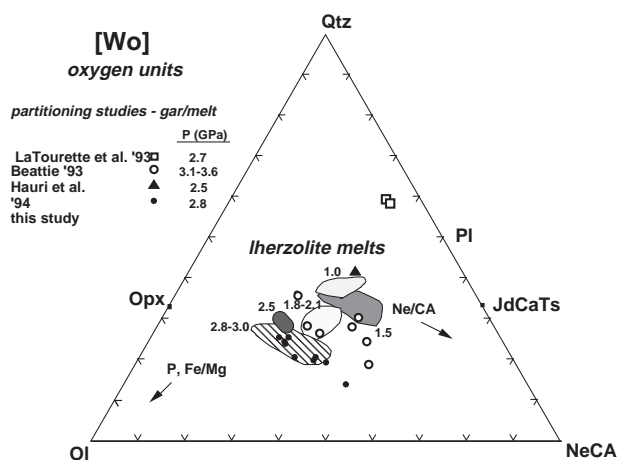
Figure 1. Comparison of liquids in equilibrium with lherzolite assemblages up to 30 kb (shaded fields) and liquids produced in studies of U-Th partitioning between garnet and liquid (individual points - see legend). Compositions are projected from wollastonite (CaSiO$_3$) component onto the Ol({Mg,Fe}$_2$SiO$_4$)-Ne(NaAlSiO$_4$)CA(CaAl$_2$O$_4$)-Qtz(SiO$_2$)

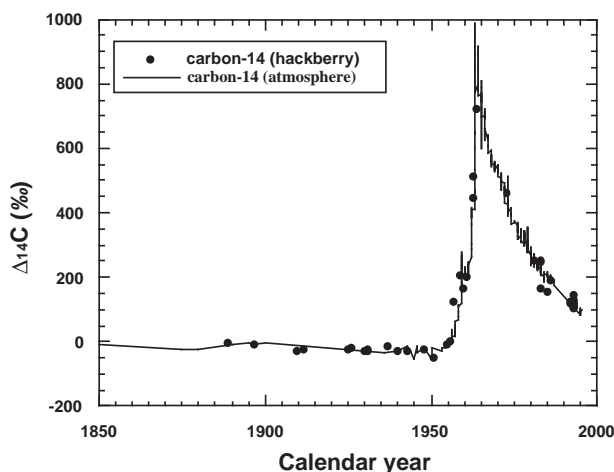*References:*

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Figure 1. Comparison of the radiocarbon content of biogenic carbonate in hackberry seeds (solid dots) with the ^{14}C levels of the atmosphere (Suess, 1955; Stuiver, 1965; Levin *et al.*, 1985; Manning *et al.*, 1990).

Potential for Radiocarbon Dating of Biogenic Carbonate in Hackberry (*Celtis*) Seeds

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Hackberry seed (Celtis sp.) contains significant amounts of biogenic carbonate. X-ray diffraction has revealed that the biogenic carbonate in hackberry seed is nearly pure aragonite. Because of high mineral content, hackberry seeds are found abundantly in Tertiary and Quaternary sediments, and are very common in many North American archaeological sites. In this study, we analyzed the radiocarbon content of different components of modern hackberries including the biogenic carbonate in hackberry seeds collected at known times over the last century. Our results show that the radiocarbon content of biogenic carbonate in hackberry seeds accurately records the radiocarbon content of the atmosphere (Figure 1). Radiocarbon dates of biogenic carbonate in fossil seeds compared favorably with dates obtained by other means at archaeological and geological sites ranging in age from the late Pleistocene through the early Holocene. We therefore suggest that biogenic carbonate in hackberry seed is a suitable substrate for radiocarbon dating provided that its morphological and mineralogical integrity is preserved.

EPR Investigations in Quartz Dosimetry

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Stored within the crystalline and electronic structure of quartz is information regarding its radiation, thermal, and light exposure history. In 1997 efforts continued to develop an understanding of how and where this information is stored, and how it is best retrieved. The studies have concentrated on the growth, decay, and charge competition of the electron paramagnetic centers E_1', $[GeO_4/Li]^+$, $[AlO_4]^o$, a peroxy-radical center, and a related non-bridging oxygen hole center(NBOHC). Paul Levy and Jim Kierstead of the Brookhaven National Laboratory performed the ultra-high γ radiations necessary to duplicate dose levels reached in natural quartz by ambient radiation levels over geologic time. Arrhenius extrapolation of isothermal and isochronal laboratory heating experiments to a geologic time scale is providing information about annealing kinetics and the likelihood of developing a quartz chronometer and geothermometer.

The E_1' center, for example, is found to have a room temperature mean life of close to a half-billion years;

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the peroxy radical and NBOHC are even more stable. For quartz samples that have been subjected to low natural radiation doses (geologically young quartz), the dose sensitivity (growth of EPR centers) is dominated by electron and hole trap filling. The growth rate of EPR centers in old quartz is dominated by the slower process of trap formation, and here annealing rates also become important. Simultaneous consideration of experimentally determined dosimetric and annealing kinetics have now demonstrated the feasibility of dosimetric dating of natural quartz, although problems remain.

In 15-minute heating experiments of quartz, there is initially an increase in the intensity of E'_1 center (presumably this is due to the trapping of holes released from the much less stable $[AlO_4]^o$). This increases up to some maximum value until, at a temperature of 300 °C, the signal begins to decay. The temperature at which this maximum value is reached depends on the length of the heating event. At low enough temperature (preliminary results indicate that this might be as high as 100 °C), $E'_{1(max)}$ will never be reached in typical geologic environment, for the annealing rates then might become slower that the rate of new trap formation. At 150 °C, the maximum signal is obtain within one year.

A quartz geothermometer sensitive to temperatures between 100 °C and 150 °C would be of great value in petroleum exploration. Quartz is a common mineral in every sedimentary basin and every petroleum reservoir. The so-called petroleum maturation window is within this 50 degree interval. Below it petroleum does not form; above it, petroleum cracks into less valuable hydrocarbons. It is hoped that our investigations, might lead to a cheap and powerful method used in assessing the petroleum potential of sedimentary basins.

Exploring the Kappa Conundrum: The Role of Recycling in the Lead Isotope Evolution of the Mantle

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The measured kappa ($^{232}Th/^{238}U$, or k) of mid-ocean-ridge basalts (MORBs) and, by inference, the Earth's upper mantle above a depth of about 670 km., is much lower than the time-integrated k recorded by Pb isotope ratios (kPb) in MORBs. Simple, quantitative considerations show that this observation can be readily explained by *in situ* decay, without invoking a decoupling of parent and daughter isotopes as invoked in previous models. Our approach requires the MORB mantle to have a roughly constant Th/U ratio during early Earth history, followed by a period of steadily decreasing Th/U from the middle of the Archean (about 3 billion years ago) to the present. Monte-Carlo modeling of mantle evolution in this context demonstrates the viability of the scenario in explaining modern-day lead isotopic signatures of MORB and OIB reservoirs. The model predicts a relatively high k of ~5 for the continental crust, and requires the recycling of crustal uranium back into the mantle during the latter half of Earth history. This preferential recycling of uranium, relative to thorium, results from the high aqueous mobility of uranium in the oxidizing environment at the Earth's surface, which leads to a transport of uranium from the continents to the altered oceanic crust and, ultimately, by subduction, back into the mantle. This process may only have become important in post-Archean time, on the order of 2 billion years ago, after a marked increase in atmospheric oxygen fugacity led to a change in the predominant surface oxidation state of uranium. The uranium fluxes required in this model of Post-Archean Uranium Recycling (PURE) are

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compatible with present-day fluxes of "excess" continental uranium into subduction zones, integrated over some 2 Ga.

U-Th Disequilibrium at Iceland: An Analog for Volcanism at Mid-Ocean Ridges

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U-series disequilibrium offers a new perspective from which to investigate melting processes beneath mid-ocean ridges. The short-lived decay products of ^{238}U can reliably be assumed to be in secular equilibrium at the onset of melting; this provides an important constraint on the initial conditions of melting that is not available for other geochemical tracers. As melting proceeds, the fractionation between ^{238}U and ^{230}Th will depend on the degree and pressure of melting, the matrix porosity, and the bulk partition coefficients for U and Th, which are influenced by the mineralogy of the source. Experimental determinations of U and Th partition coefficients in mantle minerals indicate that the two mineral phases which control U-Th fractionation in the upper mantle are garnet and clinopyroxene: Th is more incompatible than U in garnet, while in clinopyroxene, the reverse is true. Below the garnet-spinel transition, a melt of a typical mantle peridotite should be enriched in ^{230}Th relative to the parental ^{238}U, whereas melts produced at shallower depths will not show this characteristic signature.

The ^{238}U-^{230}Th system has recently been used with great success to date young volcanic rocks. Where Th-bearing phenocrysts are present, this is a fairly straightforward task that uses an "isochron" method on a plot of ($^{230}Th/^{232}Th$) vs. ($^{238}U/^{232}Th$). For mid-ocean ridge basalts (MORBs), however, determining a cooling age is not so simple because of the very low levels of U and Th present in olivine

and plagioclase phenocrysts. Goldstein and colleagues have shown that, at least in some cases, ($^{230}Th/^{232}Th$) ratios are *relatively* constant for a particular ridge segment, and that deviations from this "initial" value can be interpreted in terms of rough ages. In general, however, it does not appear that ridge-segment ($^{230}Th/^{232}Th$) uniformity is the rule, and thus dating MORBs via ^{238}U-^{230}Th systematics remains problematic.

The global mass spectrometric ^{238}U-^{230}Th database for MORBs reveals intriguing correlations of ($^{230}Th/^{238}U$) with both ridge depth, and source composition. The correlation with ridge depth is related to a deeper initiation of melting in the hotter mantle beneath shallow ridges, and a resulting stronger garnet signature in derivative melts. The apparent influence of source composition on ($^{230}Th/^{238}U$) may also be related to the presence of garnet as isotopically "enriched" sources may contain relatively higher proportions of a garnet-rich, recycled mafic component. Deconvolution of these perhaps-related effects is complicated by the poor age control, and resulting uncertainty in ($^{230}Th/^{238}U$), in most MORBs. Further, shallow ridge segments are often associated with hot spots and, therefore, axial depth and enriched source composition may be intimately, if not causally, related.

The ambiguity that results from these relationships needs to be investigated in a setting that is free of the age uncertainty inherent in many ridge basalts (for a 500m combined resolution in determination of sample and ridge axis location, an uncertainty of ~50 Ky. is inferred for a slow-spreading ridge, with a half-spreading rate of 10 mm/yr.). Such age control is a necessary step toward realizing the full potential of the ^{238}U-^{230}Th method for investigating MORB melting and the factors that influence it. We have, therefore, initiated a detailed ^{238}U-^{230}Th investigation of primitive basalts from Iceland. Though clearly not a normal ridge, the Icelandic rift system is the only place on Earth where a mature ridge exists above sea level within an ocean basin. The morphological affects of the last glaciation, which ended only about 10 Ky. ago,

even without other stratigraphic relationships, assures us of no more than 10 Ky. uncertainty when we work in the post-glacial eruptive series. Further, the very regular and well-behaved chemical and isotopic variation known to characterize Icelandic basalts provides the control that is required to carefully evaluate possible relationships between source composition and (^{230}Th/^{238}U) ratios. In light of the very high magma production rates and large range in the chemical compositions in Icelandic basalts, it is likely that melting occurs over a greater range of depths than at normal ridges. Absent the obfuscation of age uncertainty, we hope to use the results of this study to deconvolute the effects of source composition and depth of melting on (^{230}Th/^{238}U) systematics. In addition, this study provides the opportunity to better quantify the chemical and physical nature of plume-ridge interaction at Iceland. Data acquisition for this project is currently underway.

Effect of Melting Time on Uranium-Series Disequilibrium in Young Lavas

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Radioactive disequilibria between the nuclides of the Uranium series in recent lavas provide important information on magmatic processes. Previous modeling of Uranium decay series isotopes during partial melting have addressed the effects of porosity (f) and melting rate (M') on the variations of (^{230}Th/^{238}U) and (^{226}Ra/^{230}Th) in young magmas by assuming that the melting time, T, approaches infinity. The values of (^{230}Th/^{238}U)$_\bullet$ and (^{226}Ra/^{230}Th)$_\bullet$ have been used to estimate the porosity and melting rate in the mantle source. This estimate is, however, a limiting case, because of the assumption concerning melting time.

We have quantitatively investigated the effect of melting time on Uranium series disequilibria in young lavas. Three general, non-linear simultaneous equations, describing the variations of (^{230}Th/^{238}U), (^{226}Ra/^{230}Th) and (^{231}Pa/^{235}U) in magmas, as a function f, M', and T, have been deduced and shown to yield a unique set of solutions when solved using Broyden's method. We conclude that short melting times, slow melting rates, and low porosity in upwelling garnet peridotite mantle ($D_U > D_{Th}$, $D_{Th} > D_{Ra}$, $D_U > D_{Pa}$) favor the generation of lavas with large (^{230}Th/^{238}U), (^{226}Ra/^{230}Th), and (^{231}Pa/^{235}U) ratios (much larger than predicted by previous models. If melting takes place in the spinel peridotite field, ($D_{Th} > D_U$, $D_{Th} > D_{Ra}$, $D_U > D_{Pa}$), the same is true for (^{226}Ra/^{230}Th) and (^{231}Pa/^{235}U), but the reverse is true for (^{230}Th/^{238}U).

Spiegelman and Elliott (1993) have proposed that the observed (^{230}Th/^{238}U) ratios of MORBs may be produced during magma transport between the source region and the surface by equilibrium melt percolation. If the whole melting column is in the garnet peridotite stability field, and the maximum porosity at the top of the column is small, large (^{230}Th/^{238}U) ratios can be produced at the top of the melting column. However, for the MORB mantle, this may not be the case. Slow melt percolation and continuous chemical reaction with spinel peridotite en route to the surface will buffer the (^{230}Th/^{238}U) of the percolating melt close to unity (Iwamori, 1994). In addition, equilibrium melt percolation is difficult to reconcile with the extreme depletion of incompatible elements observed in abyssal clinopyroxene (Johnson *et al.*, 1990) or major element (FeO) constraints (Langmuir *et al.*, 1992). Since rapid melt transport through chemically isolated channels probably dominates through much of the regime beneath mid-ocean ridges, (^{230}Th/^{238}U), (^{226}Ra/^{230}Th) and (^{231}Pa/^{235}U) ratios in MORB will tend to be controlled by partial melting rather than by melt percolation under equilibrium conditions.